SUPERLUMINAL PARTICLES AND HIGH-ENERGY COSMIC RAYS

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ABSTRACT

Lorentz symmetry has been tested at low energy with great accuracy, but its extrapolation to very high-energy phenomena is much less well established. We expect a possible breaking of Lorentz symmetry to be a very high energy and very short distance phenomenon, compatible with existing data. If textbook special relativity is only an approximate property of the equations describing a sector of matter above some critical distance scale, superluminal sectors of matter may exist related to new degrees of freedom not yet discovered experimentally. The new superluminal particles (**"superbradyons"**) would have positive mass and energy, and behave kinematically like "ordinary" particles (those with critical speed in vacuum equal to c , the speed of light) apart from the difference in critical speed (we expect $c_i \gg c$, where c_i is the critical speed of a superluminal sector of matter). At speed $v > c$, they are expected to release "Cherenkov" radiation ("ordinary" particles) in vacuum. If superluminal particles exist, they could provide most of the cosmic (dark) matter and produce very high-energy cosmic rays compatible with unexplained discoveries reported in the literature. We discuss: a) the possible relevance of superluminal matter to the composition, sources and spectra of high-energy cosmic rays; b) signatures and experiments allowing to possibly explore such effects.

RELATIVITY, MATTER AND SUPERLUMINAL PARTICLES

Lorentz invariance can be viewed as a symmetry of the motion equations, in which case no reference to absolute properties of space and time is required and the properties of matter play the main role (Gonzalez-Mestres, 1996). In a two-dimensional galilean space-time, the equation:

$$\alpha \, \partial^2\phi/\partial t^2 \, - \, \partial^2\phi/\partial x^2 = F(\phi) \tag{1}$$

with $\alpha = 1/c_o^2$ and c_o = critical speed, remains unchanged under "Lorentz" transformations leaving invariant the squared interval:

$$ds^2 = dx^2 - c_o^2 dt^2 \tag{2}$$

so that matter made with solutions of equation (1) would feel a relativistic space-time even if the real space-time is actually galilean and if an absolute rest frame exists in the underlying dynamics beyond the wave equation. A well-known example is provided by the solitons of the sine-Gordon equation, obtained taking in (1):

$$F(\phi) = (\omega/c_o)^2 \, sin \, \phi \tag{3}$$

where ω is a characteristic frequency of the dynamical system. A two-dimensional universe made of sine-Gordon solitons plunged in a galilean world would behave like a two-dimensional minkowskian world with the laws of special relativity. Information on any absolute rest frame would be lost by the solitons, as if the Poincaré relativity principle (Poincaré, 1905) were indeed a law of Nature, even if actually the basic equation derives from a galilean world with an absolute rest frame. The actual structure of space and time can only be found by going beyond the wave equation to deeper levels of resolution, similar to the way high-energy accelerator experiments explore the inner structure of "elementary" particles. At this stage, a crucial question arises (Gonzalez-Mestres, 1995): is c (the speed of light) the only critical speed in vacuum, are there particles with a critical speed different

sible to identify at least two critical speeds: the speed of light and the speed of sound. It has been shown (Gonzalez-Mestres, 1995 and 1996) that superluminal sectors of matter can be consistently generated, with the conservative choice of leaving the Planck constant unchanged, replacing in the Klein-Gordon equation the speed of light by a new critical speed $c_i \gg c$ (the subscript i stands for the i-th superluminal sector). All standard kinematical concepts and formulas (Schweber, 1961) remain correct, leading to particles with positive mass and energy which are not tachyons. We shall call them **superbradyons** as, according to standard vocabulary (Recami, 1978), they are bradyons with superluminal critical speed in vacuum. The rest energy of a superluminal particle of mass m and critical speed c_i will be given by the generalized Einstein equation:

$$E_{rest} \ = \ m\, c_i^2 \tag{4}$$

Energy and momentum conservation will in principle not be spoiled by the existence of several critical speeds in vacuum: conservation laws will as usual hold for phenomena leaving the vacuum unchanged. Each superluminal sector will have its own Lorentz invariance with c_i defining the metric. Interactions between two different sectors will break both Lorentz invariances. Lorentz invariance for all sectors simultaneously will at best be explicit (i.e. exhibiting the diagonal sectorial Lorentz metric) in a single inertial frame (**the vacuum rest frame**, i.e. the "absolute" rest frame). In our approach, the Michelson-Morley result is not incompatible with the existence of some "ether" as suggested by recent results in particle physics: if the vacuum is a material medium where fields and order parameters can condense, it may well have a local rest frame. If superluminal particles couple weakly to ordinary matter, their effect on the ordinary sector will occur at very high energy and short distance (Gonzalez-Mestres, 1997a), far from the domain of successful conventional tests of Lorentz invariance (Lamoreaux, Jacobs, Heckel, Raab and Forston, 1986 ; Hills and Hall, 1990). In particular, superbradyons naturally escape the constraints on the critical speed derived in some specific models (Coleman and Glashow, 1997; Glashow, Halprin, Krastev, Leung and Pantaleone, 1997). High-energy experiments can therefore open new windows in this field. Finding some track of a superluminal sector (e.g. through violations of Lorentz invariance in the ordinary sector) may be the only way to experimentally discover the vacuum rest frame. Superluminal particles lead to consistent cosmological models (Gonzalez-Mestres, 1997b), where they may well provide most of the cosmic (dark) matter. Although recent criticism to this suggestion has been emitted in a specific model on the grounds of gravitation theory (Konstantinov, 1997), it should be noticed that the framework used is crucially different from the multi-graviton approach suggested in our papers.

IMPLICATIONS FOR HIGH-ENERGY COSMIC RAYS

The kinematical properties and Lorentz transformations of high-energy superluminal particles have been discussed in a previous paper (Gonzalez-Mestres, 1997c). If an absolute rest frame exists, Lorentz contraction is a real physical phenomenon and is governed by the factor $\gamma_i^{-1} \ = \ (1 \ - \ v^2 c_i^{-2})^{1/2}$ for the i-th superluminal sector, so that there is no Lorentz singularity when a superluminal particle crosses the speed value $v \ = \ c$. Similarly, if superbradyons have any coupling to the electromagnetic field, we expect the magnetic force to be proportional to $v\, c_i^{-1}$ instead of $v\, c^{-1}$. Contrary to tachyons, superbradyons can emit "Cherenkov" radiation (i.e. particles with lower critical speed) in vacuum. If $c_i \ \gg \ c$, and if the vacuum rest frame is close to that defined requiring isotropy of cosmic microwave background radiation, high-energy superluminal particles will be seen on earth as traveling mainly at speed $v \ \approx \ 10^3 \ c$. A superluminal particle moving with velocity $\vec{\mathbf{v}}$ with respect to the vacuum rest frame, and emitted by an astrophysical object, can reach an observer moving with laboratory speed $\vec{\mathbf{V}}$ with respect to the same frame, at a time (as measured by the observer) previous to the emission time. Such a phenomenon will happen if $\vec{\mathbf{v}}.\vec{\mathbf{V}} \ > \ c^2$, and the emitted particle will be seen to evolve backward in time (but it evolves forward in time in the vacuum rest frame, so that the reversal of

superluminal particles can be a directional probe preceding the detailed observation of astrophysical phenomena, such as explosions releasing simultaneously neutrinos, photons and superluminal particles. For a high-speed superluminal cosmic ray with critical speed $c_i \gg c$, the momentum, as measured in the laboratory, does not provide directional information on the source, but on the vacuum rest frame. Velocity provides directional information on the source, but can be measured only if the particle interacts several times with the detector, which is far from guaranteed, or if the superluminal particle is associated to a collective phenomenon emitting also photons or neutrinos simultaneously. In the most favourable case, directional detection of high-speed superluminal particles in a large underground or underwater detector would allow to trigger a dedicated astrophysical observation in the direction of the sky determined by the velocity of the superluminal particle(s). If d is the distance between the observer and the astrophysical object, and Δt the time delay between the detection of the superluminal particle(s) and that of photons and neutrinos, we have: $d \simeq c \, \Delta t$.

Annihilation of pairs of superluminal particles into ordinary ones can release very large kinetic energies and provide a new source of high-energy cosmic rays. Decays of superluminal particles may play a similar role. Collisions (especially, inelastic with very large energy transfer) of high-energy superluminal particles with extra-terrestrial ordinary matter may also yield high-energy ordinary cosmic rays. Pairs of slow superluminal particles can also annihilate into particles of another superluminal sector with lower c_i , converting most of the rest energies into a large amount of kinetic energy. Superluminal particles moving at $v > c$ can release anywhere "Cherenkov" radiation in vacuum, i.e. spontaneous emission of particles of a lower critical speed c_i (for $v > c_i$) including ordinary ones, providing a new source of (superluminal or ordinary) high-energy cosmic rays. High-energy superluminal particles can directly reach the earth and undergo collisions inside the atmosphere, producing many secondaries like ordinary cosmic rays. They can also interact with the rock or with water near some underground or underwater detector, coming from the atmosphere or after having crossed the earth, and producing clear signatures. Contrary to neutrinos, whose flux is strongly attenuated by the earth at energies above $10^6 \ GeV$, superluminal particles will in principle not be stopped by earth at these energies. In inelastic collisions, high-energy superluminal primaries can transfer most of their energy to ordinary particles. Even with a very weak interaction probability, and assuming that the superluminal primary does not produce any ionization, the rate for superluminal cosmic ray events can be observable if we are surrounded by important concentrations of superluminal matter. Background rejection would be further enhanced by atypical ionization properties.

The possibility that superluminal matter exists, and that it plays nowadays an important role in our Universe, should be kept in mind when addressing the two basic questions raised by the analysis of any cosmic ray event: a) the nature and properties of the cosmic ray primary; b) the identification (nature and position) of the source of the cosmic ray. If the primary is a superluminal particle, it will escape conventional criteria for particle identification and most likely produce a specific signature (e.g. in inelastic collisions) different from those of ordinary primaries. Like neutrino events, in the absence of ionization (which will in any case be very weak) we may expect the event to start anywhere inside the detector. Unlike very high-energy neutrino events, events created by superluminal primaries can originate from a particle having crossed the earth. An incoming, relativistic superluminal particle with momentum p and energy $E_{in} \simeq p \, c_i$ in the vacuum rest frame, hitting an ordinary particle at rest, can, for instance, release most of its energy into two ordinary particles with momenta (in the vacuum rest frame) close to $p_{max} = 1/2 \ p \ c_i \ c^{-1}$ and oriented back to back in such a way that the two momenta almost cancel. Then, an energy $E_R \simeq E_{in}$ would be transferred to ordinary secondaries. Corrections due to the earth motion must be applied (Gonzalez-Mestres, 1997c) before defining the expected event configuration in laboratory experiments (AUGER, AMANDA...). At very high energy, such events would be easy to identify in large volume detectors, even at very small rate. If the source is superluminal, it can be located anywhere (and even be a free particle) and will not

ray events originating form superluminal sources will provide hints on the location of such sources and be possibly the only way to observe them. The energy dependence of the events should be taken into account. At very high energies, the Greisen-Zatsepin-Kuzmin (GZK) cut-off (Greisen, 1966; Zatsepin and Kuzmin, 1966) does not in principle hold for cosmic ray events originating from superluminal matter: this is obvious if the primaries are superluminal particles that we expect to interact very weakly with the cosmic microwave background, but is also true for ordinary primaries as we do not expect them to be produced at the locations of ordinary sources and there is no upper bound to their energy around 100 EeV. Besides ”Cherenkov” deceleration, a superluminal cosmic background radiation may exist and generate its own GZK cutoffs for the superluminal sectors. However, if there are large amounts of superluminal matter around us, they can be the main superluminal source of cosmic rays reaching the earth. To date, there is no well established interpretation of the highest-energy cosmic ray events. Primaries (ordinary or superluminal) originating from superluminal particles are acceptable candidates and can possibly escape several problems (event configuration, source location, energy dependence...) faced by cosmic rays produced at ordinary sources.

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